International Journal of Computational and Experimental Science and ENgineering
(IJCESEN)
Vol. 12-No.1 (2026) pp. 77-89
http://www.ijcesen.com
ISSN: 2149-9144

Research Article

Enhancing The Performance and Sustainability of Lightweight Hebel Bricks Using Local Coco Fiber Additives: A Green Material Innovation for Circular Construction

Don R. G. Kabo[1], Miswar Tumpu[2]*, Denny B. Pinasang[3], Carter Kandou[4], Herman Tumengkol[5], Hoong-Pin Lee[6]

[1]Manado State Polytechnic, Civil Engineering Department, 95258, Manado-Indonesia
Email: donkabo74@gmail.com - **ORCID:** 0009-0008-8017-8373

[2]Hasanuddin Üniversity, The Graduate School, Disaster Management Study Program, 90245, Makassar-Indonesia
* **Corresponding Author Email:** miswartumpu@unhas.ac.id - **ORCID:** 0000-0002-4080-8114

[3]Manado State Polytechnic, Civil Engineering Department, 95258, Manado-Indonesia
Email: dennyboypinasang@yahoo.com - **ORCID:** 0009-0008-8017-8373

[4]Manado State Polytechnic, Civil Engineering Department, 95258, Manado-Indonesia
Email: ckandou@yahoo.com - **ORCID:** 0009-0008-8017-8373

[5]Manado State Polytechnic, Civil Engineering Department, 95258, Manado-Indonesia
Email: tumengkolherman@yahoo.co.id - **ORCID:** 0009-0008-8017-8373

[6]INTI International Üniversity, Faculty of Engineering and Quantity Surveying, Civil Engineering Department, 71760, Negeri Sembilan-Malaysia
Email: hoongpin.lee@newinti.edu.my - **ORCID:** 0000-0002-9122-1727

Article Info:

DOI: 10.22399/ijcesen.4490
Received : 09 November 2025
Revised : 29 Decemberr 2025
Accepted : 02 January 2026

Keywords

lightweight concrete
coco fibre
sustainable construction
green building materials
circular economy
Sustainable Development Goals (SDGs)

Abstract:

The construction industry faces increasing pressure to adopt sustainable and low-carbon materials, particularly in the production of lightweight concrete such as Hebel bricks. This study investigates the incorporation of locally sourced coco fibre, an agricultural waste derived from coconut husks, as a natural additive in Hebel brick mixtures. The novelty of this research lies in the utilization of coco fibre—abundant, biodegradable, and mechanically resilient—as both a performance-enhancing component and an ecological solution for Indonesia's construction sector. By improving the mechanical properties of lightweight bricks while promoting resource circularity, this approach contributes to green material innovation and addresses waste valorisation challenges in coconut-producing regions such as North Sulawesi.An experimental method was employed using five mix proportions with coco fibre contents of 0% (control), 0.5%, 1.0%, 1.5%, and 2.0%. Compressive strength and flexural strength tests were conducted in accordance with ASTM C109 and ASTM C348, respectively, at curing ages of 3, 7, and 28 days. The results demonstrate that compressive strength increased significantly with coco fibre addition up to an optimal content of 1.5%. At 28 days, the optimal mixture achieved a compressive strength of 3.42 MPa, exceeding the minimum requirement of 3 MPa specified by SNI 03-0349-1989 for lightweight concrete blocks. Furthermore, the bulk density of all mixtures remained below 1,000 kg/m³, confirming their suitability for non-structural lightweight construction applications.

1. Introduction

The demand for sustainable construction materials is increasing globally, as environmental impacts of conventional practices—especially those involving high-emission materials like Portland cement—are no longer acceptable [1, 2]. Autoclaved Aerated Concrete (AAC), or Hebel, has been widely promoted due to its lightweight characteristics, thermal insulation, and low dead load, which make it energy-efficient during transport and installation [3, 4]. Nevertheless, despite these benefits, its production still consumes a significant amount of cement and other inorganic binders, which contribute directly to carbon emissions [5, 6]. Thus, innovations in AAC materials that reduce environmental burdens while maintaining mechanical integrity are urgently needed.

Natural fibres have gained traction in concrete research as they offer renewable, biodegradable, and locally abundant alternatives to synthetic reinforcements. Coco fibre, derived from coconut husks, is one of the most promising options due to its high tensile strength, moisture resistance, and strong bonding with cementitious matrices [7]. In regions like Indonesia—one of the top coconut producers globally—the reuse of coco fibre supports both environmental and socio-economic goals through waste valorisation and rural material innovation [8]. Compared to industrial fibres such as polypropylene or steel, coco fibre has a much lower embodied energy and carbon footprint [9].

Previous studies on lightweight concrete have validated the performance-enhancing role of natural fibres in foam concrete and prefabricated systems. Amiruddin et al. [10] showed that prefabricated foam concrete infill walls reinforced with fibre exhibited better cyclic loading resistance. Similarly, Parung et al. [11] observed more stable crack patterns and delayed failure modes in fibre-modified lightweight concrete under compression and tension. Comparable results were also found in global studies, such as those by Akbulut, Z.F. et al. [12], who demonstrated improved ductility and post-peak behaviour in fibre-reinforced lightweight concrete panels, indicating global consensus on the structural benefit of fibre integration.

Despite this progress, most published studies have been limited to foamed concrete or non-autoclaved systems. Investigations that explore the behaviour of coco fibre within the specific thermal and chemical environment of AAC remain scarce, particularly under standard curing and testing protocols such as ASTM C109 [13] or SNI 03-0349-1989 [14]. Mansyur et al. [15] emphasized the importance of loading configuration and matrix structure in evaluating concrete response, yet few studies have applied such principles to coco fibre-AAC composites. Compared to broader international efforts—such as Kumbasaroglu, H. and Kumbasaroglu, A. [16], who synthesized data on agro-waste in concrete—the Indonesian context remains underrepresented in this field.

To contribute to this underexplored field, the present study proposes the use of coco fibre as a performance-enhancing additive in AAC production. Drawing from the sustainability-oriented material frameworks discussed by Koval, V. et al. [17] and Nawab, M.S. et al. [18], this research examines how coco fibre can reduce cement consumption and increase matrix strength through improved microstructural integrity. By focusing on a locally sourced bio-additive, this work supports both environmental sustainability and regional economic empowerment. The significance of this study lies in its interdisciplinary positioning: combining engineering performance, environmental responsibility, and the practical application of circular economy principles.

Although coco fibre has been explored in conventional mortar and concrete mixtures, its behaviour in AAC systems remains uncertain due to differences in material porosity, curing temperature, and aeration chemistry. The dual role of coco fibre in improving mechanical properties while contributing to low-carbon development requires empirical validation through rigorous, standardized testing. Compared to more mature fibre applications in international studies [19], Indonesia still lacks systematic evaluations of natural fibre integration in AAC-type bricks. This presents a clear research gap in experimental, region-specific development of bio-based lightweight materials.

In light of this, the present study aims to investigate the potential of coco fibre as an ecological and structural additive in the production of Hebel bricks. The objective is to evaluate the influence of varying coco fibre contents on the mechanical performance of AAC blocks under standardized laboratory procedures. Through this, the research seeks to contribute to the advancement of high-performance green building materials and to reinforce the transition to sustainable, circular construction systems. The main objective is to validate coco fibre-enhanced AAC as a viable lightweight alternative that meets both technical and environmental benchmarks.

2. Materials and Method

2.1 Fine Aggregate (Silica Sand)

Fine aggregate, commonly referred to as sand, plays a critical role in the composition and performance of concrete mixtures. It fills voids between coarse particles, enhances the workability of fresh concrete, and influences the strength, durability, and density of the hardened product. The physical characteristics of fine aggregate—such as fineness modulus, particle shape, and cleanliness—can significantly affect bonding with the cement matrix and overall material performance. In lightweight concrete systems like Autoclaved Aerated Concrete (AAC), the selection of fine aggregate must also consider its compatibility with gas-forming agents and its effect on the porosity of the matrix. For this study, highpurity silica sand was selected as the fine aggregate due to its uniform gradation and compatibility with coco fibre-modified AAC formulations. The properties of the fine aggregate used in this study are presented in Table 1.

Table 1. *Physical properties of fine aggregate (silica sand)*

Property	Test Method	Result	Requirement (SNI 03-2834-2000) [20]
Fineness Modulus	ASTM C136 [21]	2.58	2.3 – 3.1
Specific Gravity (SSD)	ASTM C128 [22]	2.64	2.5 – 2.8
Water Absorption (%)		1.22	≤ 3.0
Silt Content (%)	SNI 03-4142-1996 [23]	2.1	≤ 5.0
Bulk Density (kg/m³)	ASTM C29 [24]	1520	–

Based on the results shown in Table 1, the silica sand used as fine aggregate meets the standard requirements outlined in SNI 03-2834-2000 [20]. The fineness modulus of 2.58 indicates a well-graded sand suitable for concrete applications, offering an optimal balance between workability and strength development. A specific gravity of 2.64 is within the typical range for natural silica, suggesting stability in the mix. The relatively low water absorption of 1.22% contributes to better control over the water-cement ratio, which is essential in lightweight concrete systems. Furthermore, the silt content of 2.1% is well below the maximum limit, minimizing potential bond interference between the sand and cementitious matrix. Overall, these characteristics support the selection of this fine aggregate for producing consistent, high-performance coco fibre-reinforced AAC blocks.

2.2 Portland Composite Cement (PCC)

Portland Composite Cement (PCC) is a type of blended cement formulated by combining Ordinary Portland Cement (OPC) with various mineral additives such as fly ash, pozzolan, or limestone. PCC is widely used in construction due to its improved workability, lower hydration heat, and environmental advantages from reduced clinker content. Its suitability for lightweight concrete production lies in its ability to enhance matrix cohesiveness and long-term strength development, while also contributing to the sustainability of construction practices. The chemical and physical properties of PCC significantly influence the setting time, compressive strength, and compatibility with other constituents like natural fibres. In this study, PCC Type I produced by a nationally certified manufacturer was used, and its properties were evaluated in accordance with SNI and ASTM standards to ensure compliance and consistency in AAC-based brick formulations. The physical and chemical characteristics of the Portland Composite Cement used in this study are shown in Table 2.

Table 2. *Physical and chemical properties of Portland Composite Cement (PCC)*

Property	Test Method	Result	Requirement (SNI 15-7064-2014) [25]
Physical Properties			
Fineness (Residue on 45 µm) (%)	ASTM C430 [26]	6.2	≤ 10
Setting Time - Initial (minutes)	ASTM C191 [27]	104	≥ 60
Setting Time - Final (minutes)		210	≤ 600
Soundness (Le Chatelier, mm)	ASTM C151 [28]	1.0	≤ 10
Specific Gravity	ASTM C188 [29]	3.12	3.1–3.2
Chemical Properties			
SiO_2 (%)	XRF Analysis	22.4	–
Al_2O_3 (%)		6.1	–
Fe_2O_3 (%)		3.9	–
CaO (%)		62.3	–
MgO (%)		2.4	≤ 5
SO_3 (%)		2.6	≤ 3.5
Loss on Ignition (%)	ASTM C114 [30]	2.1	≤ 5

As shown in Table 2, the Portland Composite Cement used in this research meets the standard requirements for physical and chemical performance based on SNI 15-7064-2014 [25]. The fineness of 6.2% residue indicates sufficient surface area for hydration reactions, which is essential for strength gain in lightweight AAC systems. The initial and final setting times are within the allowable range, ensuring workable open time and early matrix stability. The soundness test result (1.0 mm) confirms volume stability, which is critical to avoid expansion-related cracking. From a chemical standpoint, the high CaO content (62.3%) supports adequate strength development, while moderate levels of SiO_2 and Al_2O_3 enhance the pozzolanic reaction, especially in the presence of coco fibre.

The MgO and SO_3 contents are below the maximum thresholds, indicating low risk of deleterious expansion or sulphate attack. These properties validate the use of PCC in the fibre-reinforced AAC brick formulation and ensure its compatibility with both autoclaved and natural curing methods.

2.3 Coco Fibre

Coco fibre, also known as coir, is a robust natural fibre extracted from coconut husk and characterized by high lignin content and notable tensile strength—ranging between 175–220 MPa with an elongation of 15–30% (Coco fibre density ≈1.2 g/cm³). Its coarse, rough surface facilitates strong mechanical interlocking with cementitious matrices, improving bond behaviour and crack resistance in composite materials. Coir's hydrophobic and textured morphology, observable under SEM, increases adhesion with cement and contributes to enhanced flexural toughness and post-cracking ductility in fibre-reinforced concrete. The physical properties of coco fibre used in this study are summarized in Table 3 and Figure 1 shows the physical appearance of coco fibre.
Figure 1 (photo of raw coco fibre) shows the fibrous bundles featuring coarse, uneven surfaces and occasional pith residues, indicating untreated morphology typical of brown coir fibres. Figure 2 (SEM micrograph of fibre surface morphology) reveals pronounced surface pits and rough ridges, enhancing cement paste anchorage and mechanical interlock. The SEM features—including micro-pits and fibrillar structures—are consistent with literature indicating that such surface characteristics promote stronger bonding with cement hydration products, improving post-crack ductility and energy absorption in fibre-reinforced composites.

Table 3. *Physical properties of coco fibre*

Property	**Test Method**	**Result**	**Standard/Typical Range**
Fiber Diameter (µm)	Optical Microscopy	600 ± 50	~500–700 µm
Moisture Content (%)	Oven drying	12.4	≤ 15
Bulk Density (kg/m³)	ASTM D2395	210	~200–250
Tensile Strength (MPa)	Single fibre tensile	195	175–220
Elongation at Break (%)	Single fibre tensile	22	15–30

Figure 1. *Physical appearance of coco fibre*

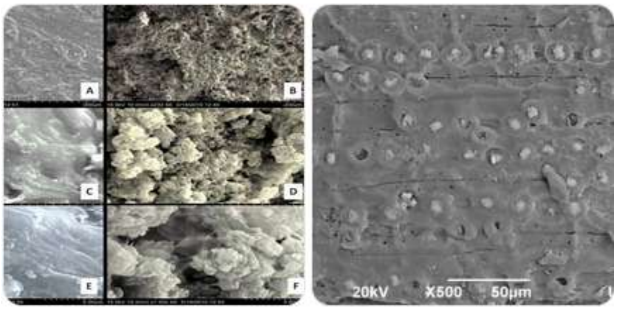

Figure 2. *SEM micrograph of coco fibre surface morphology*

Figure 2 presents the Scanning Electron Microscope (SEM) image of the coco fibre surface, revealing a highly irregular, rough, and grooved morphology. The surface is characterized by micro voids, longitudinal fibrils, and ridged textures, which are typical of untreated natural coir fibres. This microstructural roughness significantly enhances mechanical interlocking between the fibre and cementitious matrix, promoting stronger physical adhesion. The presence of these fibrillar structures provides more anchoring sites for cement hydration products, effectively delaying crack propagation and improving post-cracking performance. Similar findings were reported by Ahmad, J. et al. [31] and Noor Azman et al. [32], who observed that such surface features improve flexural toughness and ductility in fibre-reinforced lightweight concrete. Thus, the SEM analysis confirms the coco fibre's suitability as a natural reinforcing agent in sustainable construction composites such as autoclaved aerated concrete (AAC).

2.4 Research Method

This study employed an experimental laboratory approach to investigate the influence of coco fibre addition on the mechanical properties of lightweight autoclaved aerated concrete (AAC)-type bricks. The experiment was conducted at the Eco Material

Laboratory of Manado State Polytechnic, using Portland Composite Cement (PCC), fine silica sand, water, and coco fibre as the primary materials. Five different mix variations were prepared based on the proportion of coco fibre by weight of the total binder: 0% (control), 0.5%, 1.0%, 1.5%, and 2.0%. The coco fibre used was manually cleaned, dried, and cut to a uniform length of approximately 2 cm before being integrated into the mixture. The materials were dry mixed to achieve uniform distribution before the addition of water to reach the desired workability suitable for AAC-type formation.

The fresh concrete mixtures were poured into moulds to produce two types of test specimens. For compressive strength testing, cube moulds of 50 mm × 50 mm × 50 mm were used in accordance with ASTM C109. For flexural strength testing, prismatic moulds measuring 40 mm × 40 mm × 160 mm were prepared according to ASTM C348 [33]. All specimens were demoulded after 24 hours and then subjected to air curing at room temperature (±28–30°C) for three different curing periods: 3 days, 7 days, and 28 days, to simulate real-world non-autoclaved AAC applications and assess early to mature age performance. Each variation and curing age included three replicate samples to ensure statistical consistency.

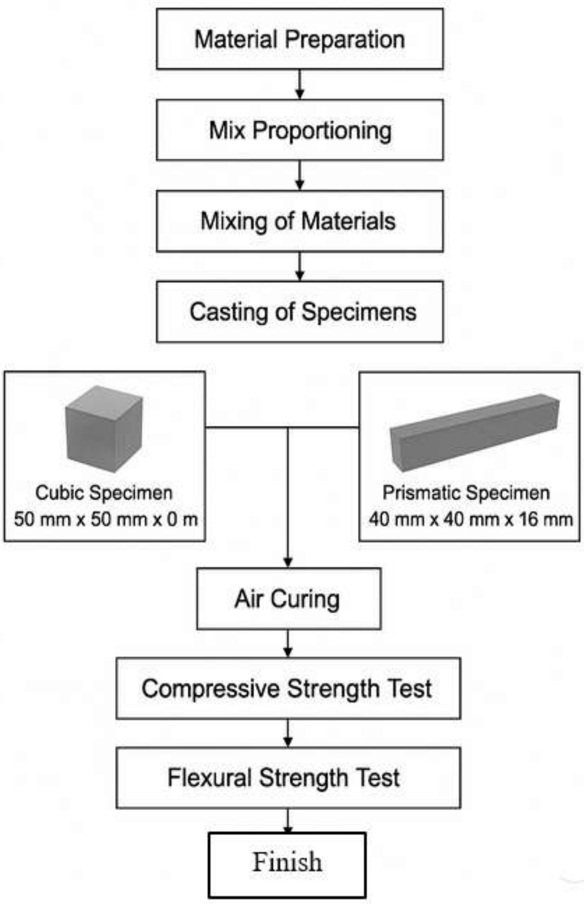

Figure 3. *Flowchart of the experimental procedures*

After curing, the mechanical tests were performed to evaluate the compressive strength and flexural strength of each variation at their respective ages. The compressive strength results were compared with the minimum standard requirements for lightweight bricks based on SNI 03-0349-1989 [14], which stipulate a minimum compressive strength of 3 MPa. In addition to strength testing, the bulk density of the specimens was also measured to verify their classification as lightweight concrete material (≤1800 kg/m³). The results of this experimental setup were analysed to determine the optimal coco fibre content that yields adequate mechanical performance while maintaining lightweight characteristics suitable for eco-friendly and sustainable construction. Figure 3 shows the flowchart of the experimental procedures.

3. Results and Discussion

3.1 Mixtures Design

In this experimental study, five different mixtures were designed to investigate the influence of local coco fibre content on the mechanical and physical performance of lightweight Hebel bricks. The mixture proportions were based on the total binder weight, with coco fibre added at incremental percentages of 0%, 0.5%, 1.0%, 1.5%, and 2.0%. All other components—Portland Composite Cement (PCC), silica sand, and water—were held constant to isolate the effect of the fibre content. The coco fibre was manually processed (cleaned, dried, and cut to 2 cm) to ensure uniformity and effective dispersion within the mixture. A consistent water-to-binder ratio was maintained across all mixtures to ensure comparable workability and hydration conditions. This mixture design allows for a systematic evaluation of the effect of fibre dosage on strength development, density, and sustainability attributes of the bricks. The detailed mixture proportions for each variation of the test specimens are presented in Table 4, which outlines the quantity of each constituent material per batch, adjusted to a standardized total binder weight.

Table 4 presents the mix proportions of lightweight Hebel bricks incorporating varying percentages of coco fibre as a natural additive. All mixtures were formulated using a constant binder weight of 500 grams and a fixed water-to-binder ratio of 0.60 to ensure consistent workability and hydration conditions across specimens. As the percentage of coco fibre increased from 0.5% to 2.0%, the absolute weight of the fibre ranged from 2.5 to 10 grams, while the amounts of cement and sand remained unchanged. This approach enabled the isolation of coco fibre's effect on mechanical performance without introducing variables from binder or aggregate variations. The gradual increment in fibre content was selected to identify the optimal dosage threshold at which performance enhancement peaks before any decline due to fibre clustering or dispersion issues. This standardized mixture design provides a robust framework for assessing the structural and environmental contributions of natural fibre reinforcement in sustainable lightweight construction materials.

3.2 Workability (Slump Test)

Workability is a critical parameter in evaluating the fresh properties of concrete, particularly in lightweight mixtures that incorporate fibrous additives. It describes the ease with which the concrete can be mixed, placed, and compacted without segregation. In this study, the slump test was performed in accordance with ASTM C143 [34] to assess the effect of varying coco fibre content on the workability of the Hebel brick mixtures. Since natural fibres are known to absorb water and influence the internal cohesion of the mix, monitoring the slump values provides insight into the practical handling and consistency of the modified concrete. All mixtures maintained a constant water-to-binder ratio of 0.60, ensuring that any changes in slump are attributed solely to the addition of coco fibre. The results of the slump test for each mixture variation are summarized in Table 5, which illustrates the decline in workability with increasing fibre content.

As shown in Table 5, the slump values of the Hebel brick mixtures exhibited a consistent decreasing trend with the increase in coco fibre content. The control mixture (M0) showed a moderate workability with a slump of 75 mm, while the highest fibre content (2.0%) resulted in a significantly lower slump of 35 mm, indicating very low workability. This reduction can be attributed to the water-absorbing characteristics of the natural fibres, which reduce the amount of free water available in the mix, and their physical tendency to entangle and obstruct the flow of the paste. The fibrous network created by higher coco fibre content also increases internal friction, further decreasing the mix's plasticity. These findings highlight the need to balance performance benefits with practical limitations in mixing and casting, especially when fibre content exceeds 1.5%.

Table 4. *Mixtures design for lightweight Hebel bricks with coco fiber additives*

Mixture Code	Coco Fiber Content (% of binder weight)	PCC (g)	Silica Sand (g)	Coco Fiber (g)	Water (g)	Water/Binder Ratio
M0 (Control)	0.0%	500	1500	0	300	0.60
M1	0.5%			2.5		
M2	1.0%			5.0		
M3	1.5%			7.5		
M4	2.0%			10.0		

Note: The total binder weight is 500 g, and coco fibre weight is calculated as a percentage of the binder.

Table 5. *Slump test results of coco fiber-reinforced Hebel brick mixtures*

Mixture Code	Coco Fiber Content (% by binder weight)	Slump Value (mm)	Workability Classification
M0 (Control)	0.0%	75	Medium
M1	0.5%	65	Medium
M2	1.0%	55	Low
M3	1.5%	45	Low
M4	2.0%	35	Very Low

3.3 Compressive Strength Performance

Compressive strength is a primary indicator of the structural viability of lightweight concrete products, including Hebel bricks. In this study, the effect of coco fibre addition on compressive strength was evaluated at three curing ages: 3, 7, and 28 days. The purpose was to assess how the incorporation of natural fibres influences early-age strength development and long-term structural integrity. The test followed ASTM C109 [13], using cube specimens cured in ambient conditions. By comparing five different mixture variations (0% to 2.0% fibre content), the progression of compressive strength over time was analysed, providing insight into both the mechanical enhancement and limitations of coco fibre-reinforced lightweight concrete systems. Figure 4 presents the compressive strength values of the Hebel brick specimens across all curing ages and fibre content variations. The results at 3 and 7 days show a clear trend:

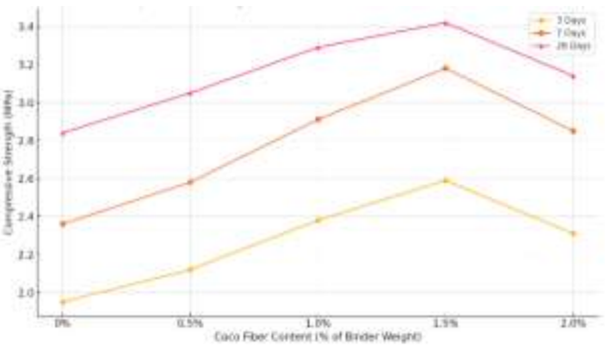

Figure 4. *Compressive strength of Hebel brick mixtures with coco fibre*

compressive strength increases with coco fibre addition up to 1.5%, followed by a decrease at 2.0%. At day 3, the control sample (0%) reached 1.95 MPa, whereas the 1.5% variation (M3) achieved 2.59 MPa—an improvement of over 32%. A similar pattern was observed at day 7, with the 1.5% sample reaching 3.18 MPa compared to 2.36 MPa in the control, indicating that coco fibre significantly contributes to early-age strength development.

This improvement in early strength is likely due to the fibre's role in forming a denser internal microstructure, reducing microcracks and bridging gaps during the initial hydration process. The rough surface and high tensile capacity of the coco fibres provide micro-reinforcement that delays crack propagation even before the cement matrix fully hardens. This aligns with findings by Gunwant, D., [35], who noted that natural fibre integration leads to more stable early hydration and crack arresting behaviour in lightweight systems.However, at 2.0% fibre content, the strength slightly declined to 2.31 MPa at day 3 and 2.85 MPa at day 7. This suggests diminishing returns due to fibre agglomeration or poor dispersion. Excess fibre content may introduce voids or interfere with cement-fibre bonding, a phenomenon similarly reported by Zhang, J. et al. [36], who observed performance drops at high fibre percentages in lightweight cementitious panels. Thus, optimal dosing is critical in fibre-based reinforcement strategies.At 28 days, the compressive strength results show that 1.5% coco fibre produced the highest strength (3.42 MPa), surpassing the SNI 03-0349-1989 [14] minimum standard of 3.0 MPa for lightweight concrete blocks. This confirms that coco fibre does not only aid in early hydration but also supports long-term strength development. In contrast, the control mixture only reached 2.84 MPa, underscoring the beneficial effect of fibre inclusion.The strength enhancement at 28 days can be attributed to improved microstructural integrity and enhanced bonding between the fibre and cement matrix. The bridging mechanism provided by the fibres reinforces the matrix against delayed crack formation and shrinkage stresses. Similar conclusions were drawn by Kumar, P. et al. [37] and Momshad, A. M. et al. [38], who emphasized the post-peak ductility and matrix-fibre adhesion as key contributors to long-term performance in natural fibre-reinforced cement composites.

In summary, while early-age gains are valuable for construction speed and handling, the mature strength performance is more relevant for structural applications. This study demonstrates that 1.5% coco fibre strikes the optimal balance between enhancing mechanical performance and maintaining appropriate material workability. It highlights the potential of locally sourced fibres to improve the sustainability and functionality of green construction materials in tropical, resource-abundant regions.

3.4 Flexural Strength Evaluation

Flexural strength is a critical parameter in evaluating a concrete's ability to resist bending and cracking under tensile stress. In fibre-reinforced systems, flexural strength also indicates the ductility and post-cracking behaviour of the material. This study examined the effect of local coco fibre additions on the flexural performance of Hebel bricks at 3, 7, and 28 days of curing. All specimens were tested using prismatic moulds in accordance with ASTM C348 [33]. By comparing five mixture variations, the study assessed how fibre content influences early crack resistance and long-term toughness. These insights are essential for understanding how coco fibre contributes not only to compressive performance but also to the structural resilience of lightweight building materials. Figure 5 illustrates the flexural strength of Hebel brick specimens reinforced with various percentages of coco fibre over three curing periods.

The results across 3, 7, and 28 days revealed a flexural strength trend similar to compressive strength. The control mixture (0%) had the lowest values at each age, while the 1.5% coco fibre mixture consistently exhibited the highest strength. At 28 days, the flexural strength increased from 0.62 MPa in the control to 0.86 MPa in the M3 mixture (1.5% fibre), representing a 38.7% improvement. This trend demonstrates the positive influence of fibre inclusion on the tensile capacity and crack resistance of the material.The flexural resistance increase is closely associated with the bridging effect of fibres that arrest crack initiation and propagation. Fibers in the 1.0% and 1.5% range provided significant improvements in flexibility and energy absorption, resulting in delayed crack development under bending loads. These results are consistent with observations by Beskopylny, A.N. et al. [39], who reported improved flexural strength in autoclaved aerated concrete panels reinforced with natural fibre additives. The study noted that fibre content in the optimal range enhances mechanical bonding and reduces brittleness.In contrast, the 2.0% fibre mixture showed a slight reduction in flexural strength compared to the 1.5% variation, dropping from 0.86 MPa to 0.77 MPa. This decline is likely due to fibre clumping, which creates weak zones and reduces uniform stress distribution. Excessive fibre content also increases internal friction and reduces paste fluidity, which hinders compaction and interfacial bonding. This behaviour has been similarly reported by Barman, N. K. et al. [40], who found that over-reinforcement with coir fibres in cement composites reduced performance due to dispersion inefficiencies.

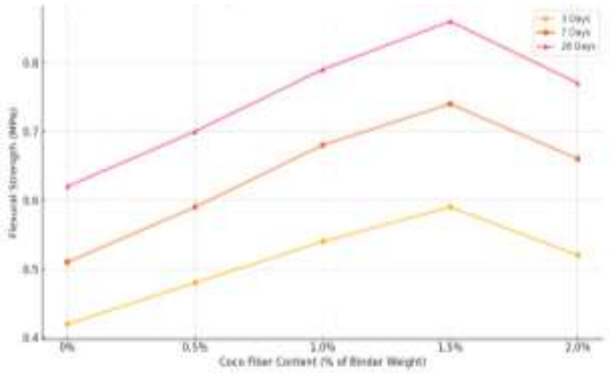

Figure 5. *Flexural strength of Hebel brick mixtures with coco fibre*

The contribution of coco fibre to post-cracking behaviour is particularly evident in the SEM micrographs (see Figure 2). The rough, fibrillated surface morphology of the fibre enhances mechanical interlocking with the cement paste, creating a bridging mechanism that transfers stress across cracks even after the matrix fails. This toughening mechanism significantly improves energy dissipation and ductility, especially in lightweight AAC systems where brittleness is a key limitation.Such behaviour aligns with the findings of Carlesso, D.M. et al. [41], who emphasized the importance of fibre-matrix bonding in enhancing post-peak performance. The physical interlock from surface textures, as seen in the SEM analysis, supports the idea that untreated coco fibres can serve as natural crack arrestors. In combination with proper fibre length and distribution, they form a discontinuous reinforcement system that mimics the behaviour of synthetic fibres with far less embodied energy.

3.5 Bulk Density and Lightweight Classification

Bulk density is an essential parameter in evaluating whether a concrete mixture qualifies as lightweight according to standard classification systems. In the context of Autoclaved Aerated Concrete (AAC) and its variants, a bulk density below 1,000 kg/m³ is generally considered suitable for non-structural lightweight applications, such as wall panels and partition blocks. In this study, bulk density measurements were carried out at 3, 7, and 28 days for all mixture variations to assess the effect of coco fibre inclusion on the overall mass and classification of the material. Since coco fibre has a much lower density than conventional mineral aggregates, its incorporation is expected to alter the internal structure of the matrix and affect air content. Understanding this influence is critical for determining the applicability of the material in lightweight construction systems. Table 6 shows bulk density results of Hebel brick mixtures at different curing ages.The results presented in Table 6 indicate a consistent decline in bulk density across all curing ages as the percentage of coco fibre increased. At 28 days, the control mixture recorded a density of 972 kg/m³, while the 2.0% fibre variation dropped to 917 kg/m³. This trend demonstrates that even modest additions of low-density natural fibre significantly reduce the overall weight of the AAC-type brick. All tested mixtures remained below the threshold of 1,000 kg/m³, thereby meeting the criteria for lightweight concrete classification as defined in SNI 03-0349-1989 [14] and aligned with ASTM standards.The reduction in bulk density can be attributed to two main mechanisms: first, the physical replacement of relatively dense mineral particles with lightweight coco fibre, and second, the entrainment of air within the matrix due to the rough, porous morphology of the fibre structure. As supported by SEM observations, the irregular texture of the fibre promotes internal air pockets, contributing to lower overall mass. Similar findings were reported by Haque, M.I. et al. [42] and Ramadan, R. et al. [43], where the inclusion of natural plant fibres in cementitious matrices resulted in reduced density due to entrapped air and increased pore volume.Moreover, the density reduction does not appear to compromise the strength significantly, particularly at optimal fibre dosages of 1.0–1.5%. This balance between mass reduction and mechanical integrity supports the argument made by Huang, Y. et al. [44] on the viability of alkali-activated and natural fibre-reinforced materials for sustainable lightweight construction. The results from this study confirm that coco fibre-reinforced Hebel bricks not only satisfy lightweight requirements but also enhance performance in a way that aligns with international research on green and efficient material innovation.

Table 6. *Bulk density results of Hebel brick mixtures at different curing ages*

Mixture Code	Coco Fiber Content (% by binder weight)	Bulk Density at 3 Days (kg/m³)	Bulk Density at 7 Days (kg/m³)	Bulk Density at 28 Days (kg/m³)
M0 (Control)	0.0%	940	960	972
M1	0.5%	928	945	958
M2	1.0%	915	934	947
M3	1.5%	898	920	932
M4	2.0%	883	906	917

3.5 Correlation Between Fiber Content and Mechanical Properties

The experimental results demonstrate a clear non-linear correlation between coco fibre content and the mechanical properties of Hebel bricks, particularly in terms of compressive and flexural strength. Initially, increasing the fibre content from 0% to 1.5% led to a steady improvement in mechanical performance, with the most significant gains observed between 1.0% and 1.5%. However, further increasing the fibre content to 2.0% resulted in a decline in both compressive and flexural strength values. This indicates that the relationship between fibre dosage and mechanical properties follows a parabolic trend rather than a linear one, where excessive fibre content becomes detrimental beyond a critical threshold.

The optimal performance at 1.5% fibre content can be attributed to the balance between effective fibre dispersion and sufficient matrix continuity. At this dosage, the fibres are well-integrated into the cementitious matrix, contributing to crack-bridging, microstructural reinforcement, and energy dissipation without compromising workability. The mixture at 1.5% showed the highest values in both compressive strength (3.42 MPa) and flexural strength (0.86 MPa), while maintaining a bulk density within lightweight classification. This suggests that 1.5% represents the tipping point where the mechanical benefits of fibre reinforcement are maximized before adverse effects begin to manifest.

Beyond the 1.5% threshold, the mechanical properties declined due to fibre agglomeration and reduced paste mobility. At 2.0%, the increased fibre volume began to hinder proper compaction and introduced air voids, reducing the overall integrity of the matrix. The entanglement and clustering of fibres at this dosage likely disrupted the uniform stress distribution under loading and weakened the bond between the cement paste and aggregates. Similar behaviour has been observed in other studies, such as Akbulut et al. [12], who found that excessive natural fibre content in lightweight composites led to the formation of weak interfacial zones and decreased structural cohesion.

Additionally, high fibre contents also negatively affect the workability of the mixture, as indicated by the slump test results. The mixture with 2.0% fibre had the lowest slump value, which may have limited proper compaction during moulding and led to inadequate bonding and densification. These rheological limitations reinforce the idea that an optimal fibre range must be carefully established not only based on strength results but also on practical considerations during mixing, placing, and finishing. This reinforces conclusions drawn by Beskopylny, A.N. et al. [39], who highlighted that both mix rheology and mechanical interaction must be considered in fibre-reinforced concrete systems.

In conclusion, the incorporation of coco fibre into AAC-type Hebel bricks improves mechanical properties only up to a certain point, after which the benefits are offset by physical and structural limitations. The non-linear nature of the relationship highlights the need for dosage optimization based on empirical testing. The 1.5% fibre content emerges as the optimal concentration that maximizes mechanical gains while maintaining satisfactory workability and density, supporting its recommendation for eco-friendly and high-performance lightweight construction applications. These findings are consistent with global trends in fibre-reinforced cement composites and underscore the potential of locally sourced agricultural waste in green material innovation.

3.6. Sustainability and Circular Economy Perspective

The incorporation of coco fibre into Hebel bricks aligns strongly with the principles of sustainability, particularly through the valorisation of agricultural waste and the reduction of cement usage. Coco fibre, sourced from coconut husk waste, is abundantly available in Indonesia, especially in regions like North Sulawesi, which are among the largest coconut producers. By utilizing this readily available waste material, the study promotes a circular approach to resource management while minimizing the environmental burden associated with waste disposal. Moreover, the reduced reliance on cement—a high-carbon material—contributes to lowering the overall environmental impact of the construction process. This directly supports the argument made by Adeyemi, O. et al. [45], who emphasized the need for integrating locally available, low-impact materials into building systems to enhance sustainability at both the material and community level.

In terms of embodied carbon, although exact numerical life cycle analysis (LCA) was not conducted in this study, a conceptual comparison can still be drawn. Traditional AAC production involves substantial energy use and emissions due to autoclaving and the high cement content. By contrast, the mixtures in this study use non-autoclaved curing and partially replace cement mass with low-carbon, biodegradable fibre. This change conceptually reduces the embodied carbon of the final product. As noted by Kumar, P. et al. [37], any replacement of cementitious binder with lower-carbon materials—particularly those that are renewable—results in a proportionally significant carbon savings. The integration of coco fibre therefore contributes to both direct and indirect emissions reduction across the material's life cycle.

The study also reinforces the principle of material substitution, which is central to circular construction frameworks. Replacing a portion of the cement or inert filler with a renewable, biodegradable component (coco fibre) directly supports the strategy of minimizing virgin material extraction. This aligns with the findings of Fode, T.A., Jande, Y.A.C. and Kivevele, T. [46], who demonstrated that natural fibre substitutions in concrete can result in significant environmental benefits without compromising performance. Additionally, the mechanical enhancements observed in this study—particularly at the 1.5% fibre level—show that performance gains can be achieved alongside environmental improvements, strengthening the case for integrated sustainability-performance approaches in material development.

Beyond environmental benefits, this research also supports the socio-economic aspects of circularity. The use of local agricultural waste creates new demand for low-value biomass, potentially contributing to rural income generation and small-scale fibre processing industries. Kandou et al. [8] have previously noted that integrating agricultural residues into construction practices enhances both community resilience and material accessibility. In this context, Hebel bricks with coco fibre offer a dual function: reducing construction sector emissions and fostering decentralized economic opportunities in coconut-producing regions.

In summary, the study presents strong alignment with circular economy strategies through the utilization of agricultural waste, reduction of high-carbon cement content, and promotion of local supply chains. These results are consistent with global efforts reported by Noor Azman, N.E.I. et al. [32] and Vijayan et al. [19], which emphasize the convergence of performance, sustainability, and economic viability in modern green materials. As the construction industry transitions toward more regenerative and circular models, innovations such as coco fibre-reinforced lightweight bricks serve as practical and scalable solutions for low-carbon development, particularly in resource-rich tropical contexts.

4. Conclusions

Based on the experimental results and analysis, this study concludes that the integration of locally sourced coco fibre into Hebel brick mixtures effectively enhances both mechanical performance and environmental sustainability. The optimal fibre content of 1.5% by binder weight resulted in the highest compressive (3.42 MPa) and flexural strength (0.86 MPa), while maintaining bulk density below 1,000 kg/m³—fulfilling lightweight classification standards. The addition of coco fibre improved early and mature-age strength through crack-bridging and matrix reinforcement mechanisms, yet excessive content (2.0%) led to performance decline due to fibre agglomeration and reduced workability. From a sustainability perspective, the use of agricultural waste as a cement-replacing additive supports circular construction principles by reducing embodied carbon, promoting local resource utilization, and fostering rural economic value. These findings validate coco fibre-reinforced AAC bricks as a viable, green building material for eco-efficient and circular construction practices.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.

- **Author contributions:** The authors declare that they have equal right on this paper.

- **Funding information:** The authors declare that there is no funding to be acknowledged.

- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

References

[1] Tombeg, B. A., Tumpu, M., Lonan, T. P., & Sumajouw, J. A. J. (2025). Environmental performance evaluation of geopolymer concrete utilizing industrial by-products and recycled aggregates under variable thermal conditions. *Ecological Engineering & Environmental Technology*, *26*(9), 293–303. https://doi.org/10.12912/27197050/209444.

[2] Annisa, R. W. R., Wahab, A. W., Tumpu, M., Demmallino, E. B., Baharuddin, B., & Caronge, M. A. (2025). Overcoming heavy metal pollution from nickel mining wastewater in Indonesia using green chemistry activated rice husk biochar for sustainable remediation. *Ecological Engineering & Environmental Technology*, *26*(9), 278–292. https://doi.org/10.12912/27197050/209753.

[3] Dey, P., Paul, A., Dhar, M., Saha, B., & Chakraborty, S. (2025). State-of-art review and future prospects of autoclave aerated concrete for building a sustainable tomorrow. *Environmental Development and Sustainability*, *27*, 123–145. https://doi.org/10.1007/s10668-025-06194-4.

[4] Sunarno, Y., Rangan, P. R., Ambun, E., & Tumpu, M. (2024). Mechanical properties of foamed concrete (FC) using high-volume fly ash. *International Journal of GEOMATE*, *26*(118), 141–148. https://doi.org/10.21660/2024.118.g13323.

[5] Kumar, M. A., Prasanna, K., Raj, C. C., Parthiban, V., Kulanthaivel, P., Narasimman, S., & Naveen, V. (2022). Bond strength of autoclaved aerated concrete manufactured using partial replacement of fly ash with fibers: A review. *Materials Today: Proceedings*, *65*(Part 2), 581–589. https://doi.org/10.1016/j.matpr.2022.03.191.

[6] Sunarno, Y., Tumpu, M., Kandou, C., Kabo, D. R. G., Tumengkol, H., & Rangan, P. R. (2025). Strength and sustainability in concrete: The dual role of fly ash and accelerators in reducing environmental impacts. *Engineering, Technology and Applied Science Research*, *15*(3), 23260–23267. https://doi.org/10.48084/etasr.10451.

[7] Martinelli, F. R. B., Ribeiro, F. R. C., Marvila, M. T., Monteiro, S. N., Filho, F. d. C. G., & Azevedo, A. R. G. d. (2023). A review of the use of coconut fiber in cement composites. *Polymers*, *15*(5), Article 1309. https://doi.org/10.3390/polym15051309.

[8] Kandou, C., Tumpu, M., Kabo, D. R. G., & Tumengkol, H. (2025). Development of High-Performance Concrete with Advanced Materials for Sustainable Building Applications. *Engineering, Technology & Applied Science Research*, *15*(2), 21482–21487. https://doi.org/10.48084/etasr.10299.

[9] Ngui, F., Muhammed, N., Mutunga, F. M., Marangu, J., & Kınotı, I. K. (2022). A review on selected durability parameters on performance of geopolymers containing industrial by-products, agro-wastes and natural pozzolan. Journal of Sustainable Construction Materials and Technologies, 7(4), Article 5, 375–400. https://doi.org/10.47481/jscmt.1190244.

[10] Amiruddin, A. A., Parung, H., Tjaronge, M. W., Irmawaty, R., Mansyur, & Tumpu, M. (2022). Influence of prefabricated foam concrete as infill wall on the strength due to cyclic loading. *International Journal of GEOMATE*, *22*(93). https://doi.org/10.21660/2022.93.j2343.

[11] Parung, H., Tumpu, M., Tjaronge, M. W., Arwin Amiruddin, A., Walenna, M. A., & Mansyur (2023). Crack Pattern of Lightweight Concrete under Compression and Tensile Test. *Annales de Chimie: Science des Materiaux*, *47*(1), 35-41. https://doi.org/10.18280/acsm.470105.

[12] Akbulut, Z. F., Tawfik, T. A., Smarzewski, P., & Guler, S. (2025). Advancing hybrid fiber-reinforced concrete: Performance, crack resistance mechanism, and future innovations. *Buildings*, *15*(8), Article 1247. https://doi.org/10.3390/buildings15081247.

[13] ASTM International. (2020). *ASTM C109/C109M-20: Standard test method for compressive strength of hydraulic cement mortars (using 2-in. or [50-mm] cube specimens).* ASTM International.

[14] Badan Standardisasi Nasional. (1989). *SNI 03-0349-1989: Tata cara perhitungan harga satuan pekerjaan beton untuk konstruksi bangunan gedung dan perumahan.* Badan Standardisasi Nasional.

[15] Mansyur, Tumpu, M., Tjaronge, M. W., & Israil. (2025). Experimental investigation of the response of precast foam concrete under monotonic loading. *International Journal of GEOMATE*, 28(125), 19–26. https://doi.org/10.21660/2025.125.4510.

[16] Kumbasaroglu, H., & Kumbasaroglu, A. (2025). Applicability of agro-waste materials in structural systems for building construction: A scoping review. *Applied Sciences*, 15(1), 71. https://doi.org/10.3390/app15010071.

[17] Koval, V., Arsawan, I. W. E., Suryantini, N. P. S., Kovbasenko, S., Fisunenko, N., & Aloshyna, T. (2023). Circular economy and sustainability-oriented innovation: Conceptual framework and energy future avenue. *Energies*, 16(1), 243. https://doi.org/10.3390/en16010243.

[18] Nawab, M. S., Ali, T., Qureshi, M. Z., Zaid, O., Ben Kahla, N., Sun, Y., Anwar, N., & Ajwad, A. (2023). A study on improving the performance of cement-based mortar with silica fume, metakaolin, and coconut fibers. *Case Studies in Construction Materials*, 19, e02480. https://doi.org/10.1016/j.cscm.2023.e02480.

[19] Vijayan, D. S., Gopalaswamy, S., Sivasuriyan, A., Koda, E., Sitek, W., Vaverková, M. D., & Podlasek, A. (2024). Advances and applications of carbon capture, utilization, and storage in civil engineering: A comprehensive review. *Energies*, 17(23), 6046. https://doi.org/10.3390/en17236046.

[20] Badan Standardisasi Nasional. (2000). *SNI 03-2834-2000: Tata cara pembuatan rencana campuran beton normal*. Badan Standardisasi Nasional.

[21] ASTM International. (2019). *ASTM C136/C136M-19: Standard test method for sieve analysis of fine and coarse aggregates*. ASTM International.

[22] ASTM International. (2015). *ASTM C128-15: Standard test method for relative density (specific gravity) and absorption of fine aggregate*. ASTM International.

[23] Badan Standardisasi Nasional. (1996). *SNI 03-4142-1996: Tata cara pembuatan rencana campuran beton normal*. Badan Standardisasi Nasional.

[24] ASTM International. (2017). *ASTM C29/C29M-17a: Standard test method for bulk density ("unit weight") and voids in aggregate*. ASTM International.

[25] Badan Standardisasi Nasional. (2014). SNI 15-7064-2014: Semen Portland pozzolan—spesifikasi. Badan Standardisasi Nasional.

[26] ASTM International. (2013). ASTM C430-13: Standard test method for fineness of hydraulic cement by the 45-µm (No. 325) sieve. ASTM International.

[27] ASTM International. (2019). *ASTM C191-19: Standard test methods for time of setting of hydraulic cement by Vicat needle*. ASTM International.

[28] ASTM International, 2022. *ASTM C188/C188M-22: Standard test method for density of hydraulic cement*. West Conshohocken, PA: ASTM International.

[29] ASTM International. (2022). *ASTM C188/C188M-22: Standard test method for density of hydraulic cement*. ASTM International.

[30] ASTM International. (2022). *ASTM C114-22: Standard test methods for chemical analysis of hydraulic cement*. ASTM International.

[31] Ahmad, J., Majdi, A., Al-Fakih, A., Deifalla, A. F., Althoey, F., El Ouni, M. H., & El-Shorbagy, M. A. (2022). Mechanical and durability performance of coconut fiber reinforced concrete: A state-of-the-art review. *Materials, 15*(10), Article 3601. https://doi.org/10.3390/ma15103601.

[32] Noor Azman, N. E. I., Marsi, N., Yusrianto, E., Tuan Ismail, T. N. H., Mohd Rus, A. Z., Hakim Shariff, H., & Ali, A. (2025). Performance autoclaved aerated concrete of crushed coconut shell (AAC-CCS) for AAC board panels. *Semarak International Journal of Material Research, 2*(1), 52–65. https://doi.org/10.37934/sijmr.2.1.5265a.

[33] ASTM International. (2020). *ASTM C348-20: Standard test method for flexural strength of hydraulic-cement mortars*. ASTM International. ASTM International. (2020). *ASTM C348-20: Standard test method for flexural strength of hydraulic-cement mortars*. ASTM International.

[34] ASTM International. (2020). *ASTM C143/C143M-20: Standard test method for slump of hydraulic-cement concrete*. ASTM International.

[35] Gunwant, D. (2024). Moisture resistance treatments of natural fiber-reinforced composites: A review. *Composite Interfaces*, 31(8), 979–1047. https://doi.org/10.1080/09276440.2024.2303543.

[36] Zhang, J., Heath, A., Ball, R. J., & Paine, K. (2022). Effect of fibre loading on the microstructural, electrical, and mechanical properties of carbon fibre incorporated smart cement-based composites. *Frontiers in Materials*, 9, Article 1055796. https://doi.org/10.3389/fmats.2022.1055796.

[37] Kumar, P., Upadhyay, R., Sharma, K. K., et al. (2025). Mechanical performance of fiber reinforced concrete incorporating rice husk ash and brick aggregate. *Innovative Infrastructure Solutions*, 10, Article 362. https://doi.org/10.1007/s41062-025-02166-9.

[38] Momshad, A. M., Islam, M. H., Datta, S. D., Sobuz, M. H. R., Aayaz, R., Kabbo, M. K. I., & Khan, M. M. H. (2025). Assessing the engineering properties and environmental impact with explainable machine learning analysis of sustainable concrete utilizing waste banana leaf ash as a partial cement replacement. *Cleaner Engineering and Technology*, 24, 100886. https://doi.org/10.1016/j.clet.2025.100886.

[39] Beskopylny, A. N., Shcherban', E. M., Stel'makh, S. A., Mailyan, L. R., Meskhi, B., Evtushenko, A., El'shaeva, D., & Chernil'nik, A. (2023). Improving the physical and mechanical characteristics of modified aerated concrete by reinforcing with plant fibers. *Fibers*, 11(4), Article 33. https://doi.org/10.3390/fib11040033.

[40] Barman, N. K., Bhattacharya, S. S., & Alagirusamy, R. (2024). Textile structures in concrete reinforcement. *Textile Progress*, 56(1), 1–229. https://doi.org/10.1080/00405167.2023.2266930.

[41] Carlesso, D. M., Cavalaro, S. H. P., Bairán, J. M., & de la Fuente, A. (2025). Flexural fatigue performance of pre-cracked steel fibre reinforced concrete: Experimental program and design-oriented approach. *Construction and Building Materials, 467*, 140308. https://doi.org/10.1016/j.conbuildmat.2025.140308.

[42] Haque, M. I., Ashraf, W., Khan, R. I., & Shah, S. (2022). A comparative investigation on the effects of nanocellulose from bacteria and plant-based sources for cementitious composites. *Cement and Concrete Composites, 125*, 104316. https://doi.org/10.1016/j.cemconcomp.2021.104316 .

[43] Ramadan, R., Ghanem, H., Khatib, J. M., & ElKordi, A. M. (2025). Effect of plant-based natural fibers on the mechanical properties and volume change of cement paste. *International Journal of Building Pathology and Adaptation, 43*(4), 693–711. https://doi.org/10.1108/IJBPA-11-2023-0166.

[44] Huang, Y., Tan, J., Xuan, X., Wei, S., Liu, L., Yu, S., & Zheng, G. (2022). Durability of plant fiber reinforced alkali-activated composites. *Construction and Building Materials, 314*(Part B), Article 125501. https://doi.org/10.1016/j.conbuildmat.2021.125501.

[45] Adeyemi, O., Ohakawa, C., Okwandu, G., Iwuanyanwu, C., & Ifechukwu, P. (2024). Affordable housing and resilient design: Preparing low-income housing for climate change impacts. *International Journal of Applied Research in Social Sciences, 6*(9), 2179–2190. https://doi.org/10.51594/ijarss.v6i9.1585.

[46] Fode, T. A., Jande, Y. A. C., & Kivevele, T. (2024). Physical, mechanical, and durability properties of concrete containing different waste synthetic fibers for green environment: A critical review. *Heliyon*, *10*(12), e32950. https://doi.org/10.1016/j.heliyon.2024.e32950.